The first statewide stream macroinvertebrate bioassessment in Washington State with a relative risk and attributable risk analysis for multiple stressors

Chad A. Larson[1*], Glenn Merritt[1], Jack Janisch[1], Jill Lemmon[1], Meghan Rosewood-Thurman[1], Brian Engress[1], Stacy Polkowske[1], George Onwumare[2]

[1] Washington State Department of Ecology, Environmental Assessment Program, 300 Desmond Drive SE, Lacey, WA 98503, USA

[2]Washington State Department of Ecology, Environmental Assessment Program, Eastern Operations Section, 1250 West Alder Street, Union Gap, WA 98903, USA

[*] Corresponding author (chad.larson@ecy.wa.gov)

Abstract

We report results from the first statewide assessment of biological health in perennial streams in Washington State. Using a probabilistic random sampling survey design, we were able to make unbiased estimates of biological condition of macroinvertebrate communities throughout the state based on 346 sites sampled from 2009-2012. Results from randomly sampled sites were classified as either good, fair, poor in comparison with 75 regional reference sites that were sampled concurrently. We determined that approximately 34 percent of stream kilometers assessed were in poor biological condition as measured with a multi-metric index, the B-IBI. Additionally, we evaluated a variety of chemical and physical habitat stressors known to negatively influence macroinvertebrate communities and determined that poor substrate conditions were the most prevalent and important stressors impacting stream macroinvertebrates, with relative bed stability and percent sand/fines being the most prevalent. A relative risk/attributable risk analysis suggests that improving physical habitat conditions in streams, most notably a reduction in percent sand/fines, will have the greatest impact for improving biological condition for macroinvertebrate communities. It is estimated that approximately 60% stream kilometers now classified as in poor biological condition could be improved by reducing the amount of percent sand/fines in the substrate. These results are consistent with those obtained from EPA's national stream surveys and suggest that poor habitat conditions are the most prevalent stressors impacting stream macroinvertebrates in Washington State.

1. Introduction

Aquatic resources are under an increasing threat of biodiversity loss due to human modifications to the landscape and climate (Vörösmarty et al. 2010; Kuemmerlen et al., 2015; Pyne & Poff 2017). Many human activities have measureable deleterious impacts on aquatic resources, with streams particularly prone to the influences of development and agricultural practices (Allan 2004). Streams impacted by agriculture and/or urbanization are subject to modifications to the natural condition, including, but not limited to, altered flow regimes (Rosburg et al., 2017; Marshalonis & Larson 2018), loss of riparian habitat (Osborne et al. 1993), elevated delivery of fine sediments, nutrients and toxics (Paul & Meyer 2001). These factors alone or in combination can alter aquatic community structure and function (Woodward et al. 2010; Pyne & Poff 2017), beginning with replacement of sensitive taxa by more tolerant ones, followed by significant diversity loss (Dudgeon et al. 2006; Vörösmarty et al. 2010).

Evaluating biodiversity patterns in freshwater streams and rivers across broad geographic scales is necessary for elucidating questions about biodiversity loss. Monitoring programs collecting environmental data paired with biological data encompassing large spatial extents benefit from wide environmental and stressor gradients from which to make meaningful associations between stressors and biodiversity loss. Furthermore, comparison of results obtained from multiple monitoring programs encompassing various spatial scales (e.g. U.S. Environmental Protection Agency's National River and Streams Assessment (NRSA), https://www.epa.gov/national-aquatic-resource-surveys/nrsa) has great potential to inform efforts aimed at addressing biological impairment in streams and rivers. Macroinvertebrate communities are relatively good indicators of water quality and stream biological health and often the focus of monitoring efforts by agencies charged with evaluating water and habitat quality. In many applied situations, linking alterations in biological communities with environmental stressors is vital so as to give stakeholders necessary information for implementing best management practices aimed at minimizing further degradation and instigating restoration efforts. However, demonstrations of the practical implementation of successful management strategies and subsequent recovery of biological communities have thus far proven rather illusive, as there are relatively few examples documented in the literature. Therefore, there is great need for scientists to provide better practical information about the causes and consequences of biodiversity losses in streams and rivers.

Several tools have been developed for evaluating the impacts of stressors on biological communities at local (U.S. EPA 2000, 2007; Yuan and Norton 2004; http://cfpub.epa.gov/caddis) and broader regional and national scales (Van Sickle & Paulsen 2008). These types of exercises can be valuable for focusing efforts and limited resources on the practices that will be most effective at improving conditions at a local scale (see Marshalonis & Larson 2018 for a recent example). When data are available encompassing broad spatial scales, relative risk and the associated attributable risk analyses have been used in streams to link poor biological condition to environmental stressors and have great potential for informing restoration efforts (Van Sickle et al. 2006; Van Sickle & Paulsen 2008). Comparison of results of statewide assessments with those of obtained from EPA's national surveys will aid efforts to better understand the response of stream biological communities to human induced stressors across multiple scales.

In Washington State, one method for assessing the biological health of streams is with a macroinvertebrate multi-metric index, the B-IBI (Karr 1998, Morley & Karr 2001). The B-IBI is composed of 10 individual diversity metrics quantifying different components of the macroinvertebrate community (more information at: https://www.pugetsoundstreambenthos.org/About-BIBI.aspx). However, to date, there has been no statewide assessment of the biological health of perennial streams, nor evaluations determining the most frequent set of stressors impacting these streams at larger spatial scales, which has hampered efforts to develop standard protocols for addressing stream rehabilitation. Once biological impairment has been determined for a site, evaluating the most likely set of stressors contributing to poor biological condition will give decision makers the ability to focus on those stressors having the greatest potential for improving conditions (Yuan and Norton 2004).

Here, we report the first statewide evaluation of stream macroinvertebrate communities in Washington State using a probabilistic sampling design implemented by the Washington State Department of Ecology (ECY), which allows for unbiased estimates of biological condition. Our objectives were threefold: 1) determine the proportion of stream kilometers within Washington in 'good', 'fair' and 'poor' biological condition using macroinvertebrate communities as a proxy for biological health, 2) evaluate the proportion of stream kilometers in 'poor' condition for a variety of stressors known to impact stream invertebrate communities, and 3) conduct a relative risk/attributable risk analysis for establishing the most probable set of stressors impacting the biological health of macroinvertebrates in perennial streams. Establishing the status of biological health in streams across the state at various spatial scales and employing techniques that link stressors and impairment will facilitate discussions focused on addressing the maintenance and rehabilitation of biological diversity of stream communities.

2. Materials and methods

2.1. Sample frame

Using a spatially balanced probabilistic sampling design (Generalized Random Tesselation Stratified (GRTS); Stevens & Olsen 2004), 346 randomly selected sites were sampled in seven salmon recovery regions and an unlisted region in Washington State from in 2009 to 2013 (Fig. 1a; more information at: https://ecology.wa.gov/Research-Data/Monitoring-assessment/River-stream-monitoring/Habitat-monitoring/Watershed-health). Using a statewide master sample frame, random sites that were not on either tribal or Federal land were sampled. Simultaneously, 75 'minimally impacted' or targeted reference sites were also sampled across the state for the purpose of establishing expectations under minimal human influence and for setting regional thresholds (*see below*) for the variables used in the Relative Risk/Attributable Risk (RR/AR) analyses (Table 1).

2.2. Biological and chemical data

Composite samples of macroinvertebrate communities along each stream reach were collected from 0.74 square meters (8 ft^2) of surface area across 8 randomly sampled pool/riffle transects at each stream reach using a D-frame kicknet with a 500 µm net. A subsample of 500 organisms were counted and identified for each sample, typically to genus or species. All samples were processed, identified and counted by Rhithron Associates, Inc. (Missoula, Montana). In addition to collecting samples of macroinvertebrates, at the beginning of each sample visit, water samples were also collected and total phosphorus, total nitrogen, total suspended solids, and chloride concentration were measured at Washington Department of Ecology/EPA's Manchester Environmental Laboratory (https://ecology.wa.gov/About-us/Get-to-know-us/Our-Programs/Environmental-Assessment/Manchester-Environmental-Laboratory). Sediment samples were also collected at the beginning of each sample visit from three random locations in the stream reach and arsenic, copper, lead, zinc and PAHs were measured at the

Manchester Environmental Laboratory. Furthermore, at the beginning and end of each sampling visit, water temperature, dissolved oxygen, conductivity, and pH were measured with a Hach portable meter calibrated for each parameter. Turbidity of water samples was also measured with a turbidity meter.

2.3. Physical habitat metrics

Along a stream reach of a minimum of 150 meters, but typically equaling 20× average bankfull width, eleven equidistant transects across the stream channel were evaluated for a variety of factors, ranging from substrate size, counts of large woody debris, to estimates of riparian cover. For measures of substrate, ten measures of substrate size and embeddedness were evaluated across the stream channel at each of the eleven transects and additionally at eleven midpoint transects located midway between each of the other eleven transects, for a total of 220 measures of substrate along a stream reach. More detailed descriptions of all physical habitat measures collected can be found at: https://ecology.wa.gov/Research-Data/Monitoring-assessment/River-stream-monitoring/Habitat-monitoring/Habitat-monitoring-methods. Specifically for percent sand/fines, ECY measured this variable across the bankfull width of each transect and midpoint transect along a stream reach, while NRSA measures it only for the wetted width. Regression of ECY and EPA values resulted in a coefficient of 5.5, so this value was added to the recommendations for percent sand/fines from (Bryce et al. 2010).

2.4. Classification of stressor and response variables

All variables used in the RR/AR analyses were placed into one of three condition classes: good, fair, or poor at each of the random sites based on either regional thresholds established using reference sites, or from available literature sources (see Table 1). From each of three assessment regions (Fig. 1b), regional thresholds were established using the 5th and 25th percentile of the reference distribution for stressors for which values decrease with impairment, and the 95th and 75th percentiles for stressors for which values increase with impairment. Consistent with Van Sickle and Poulsen (2008), good, fair, and poor classifications represented ranges of response variables representing either: not different from, somewhat different from, and markedly different from the range of values from minimally impacted reference sites. Additionally, for each sample, several additional metrics were calculated, including a Fine Sediment Biotic Index (FSBI; Relyea et al. 2012), EPT taxa richness (sum of taxa from the Orders: Ephemeroptera, Plecoptera, and Trichoptera), taxa richness of intolerant taxa and relative abundance of tolerant taxa (information at: https://www.pugetsoundstreambenthos.org/About-BIBI.aspx#Tolerant).

2.5. Statistical analyses

All statistical analyses were performed in R, version 3.3.3 (R Core Team 2017), with adjusted spatial weights of sites, all extent estimates and RR/AR analysis implemented using spsurvey (version 3.3, Kincaid and Olsen 2016). We evaluated biological condition of random sites at three spatial scales: 1) statewide, 2) each of the seven Salmon Recovery Region and one unlisted region (Fig. 1a), and 3) three assessment regions, including western Washington, Eastern Washington and the Columbia Plateau (Fig. 1b). RR/AR analyses and stressor extents were evaluated statewide. One-way ANOVA was used to examine differences between condition categories for several biological metrics (FSBI, EPT taxa richness, intolerant taxa richness, relative abundance of tolerant taxa), with differences between factor levels evaluated with Tukey pair-wise comparisons.

3. Results

3.1. Macroinvertebrate biological health

An estimated 26,361 stream kilometers were assessed in Washington State using a probabilistic sample design. Estimates from these random samples of stream macroinvertebrate communities show that 8,869 stream kilometers (33.6%) were in poor biological condition, with 11,256 (42.7%) and 6,236 (23.7%) stream kilometers in good and fair condition, respectively (Fig. 2a). In the three assessment regions, the Columbia Plateau had the highest proportion of stream kilometers classified as poor biological condition (45.6%), with estimates for Eastern and Western Washington having similar values of 34.2% and 31.7%, respectively (Fig. 2b). Conversely, the highest proportion of stream kilometers in good biological condition were observed in Eastern and Western Washington, with 49.3% and 42%, respectively. An estimated 37.8% of stream kilometers in the Columbia Plateau are estimated to be in good biological condition. Across the salmon recovery regions, poor biological condition was highest in the unlisted portion of the state, with nearly 50% of stream kilometers assessed categorized as poor biological condition, with the Puget Sound, Snake River and Northeast regions having similar estimates of poor biological condition (Fig. 3b). The highest proportion of stream kilometers assessed in good biological condition was observed in the Lower Columbia.

3.2. Stressor extents

Of the stressors evaluated here, LRBS, percent sand/fines and total Nitrogen were the top three stressors in terms of the regional extent categorized as being in poor condition (Fig. 4). Over 50% of stream miles assessed were in poor condition for substrate, with LRBS and % sand/fines at 78% and 54%, respectively. The extent of stream kilometers in poor condition for elevated total nitrogen levels was also at 49%. Conversely, very few sites had levels of sediment metals that were considered in poor condition, with only one site categorized as poor for lead and three sites categorized as poor for copper. Additionally, none of the sites assessed had levels of total PAHs considered to be in poor condition. In the different assessment regions, the variables with the highest proportion of streams in poor condition generally came from the Columbia Plateau, with high values for TN, TP, % Embedness, LWD, slope, conductivity and sinuosity (Supplementary Fig. 1).

3.3. Relative risk/Attributable risk

A majority of the variables evaluated had relative risk ratios greater than one, with most of those having ratios between 2 and 4 (Figure 5). The variable with the highest relative risk for the B-IBI was % sand/fines. Taking into account the relative risk and extent, we obtained the attributable risk for the evaluated variables and four substrate variables had the largest attributable risk for B-IBI, with % sand/fines and LRBS having very similar values. These values can be interpreted to mean that approximately 60% (95% CI: 38-75.6%) of streams classified as currently being in poor condition could be improved to either fair or good if percent sand/fines or LRBS were improved. After the four substrate variables, proportion of canopy cover (PPNCanopy) and nutrients (total N and P, respectively) had the highest attributable risk to B-IBI.

3.4. Various biological metrics

FSBI values (high values indicate greater abundance of taxa sensitive to fine sediment deposition) were highest in streams classified as ‘good’, intermediate for streams classified as ‘fair’, and lowest in streams classified as ‘poor’ (one-way ANOVA, $F_{2,343} = 197.5$, $p \leq 0.0001$, Fig. 6a). Pair-wise comparisons revealed significant differences between all three classifications ($p < 0.05$). EPT taxa richness was highest in streams classified as ‘good’, intermediate for streams classified as ‘fair’, and lowest in streams classified as ‘poor’ (one-way ANOVA, $F_{2,343}$ = 405.0, $p \leq 0.0001$, Fig. 6b). Pair-wise comparisons revealed significant differences between all three classifications ($p < 0.05$). Taxa richness of species classified as ‘intolerant’ was highest in streams classified as ‘good’, intermediate for streams classified as ‘fair’, and lowest in streams classified as ‘poor’ (one-way ANOVA, $F_{2,343}$ = 58.3, $p \leq 0.0001$, Fig. 6c). Pair-wise comparisons revealed significant differences between all three classifications ($p < 0.05$). The relative abundance of tolerant taxa was lowest in streams classified as ‘good’, intermediate for streams classified as ‘fair’, and highest in streams classified as ‘poor’ (one-way ANOVA, $F_{2,343}$ = 8.61, p = 0.0002, Fig. 6d). Pair-wise comparisons revealed significant differences only between the ‘good’ and ‘poor’ classifications ($p < 0.05$).

4. Discussion

We report results from the most comprehensive statewide biological assessment to date of macroinvertebrate communities in Washington State using a probabilistic sampling design. Because we employed a GRTS sample design, our results should represent unbiased estimates of stream biological condition on non-federal and non-tribal lands across the state of Washington. Because we also sampled concurrently, targeted reference sites, we were able to interpret the results from our randomly sampled sites in context with expectations under minimal human impacts. It is difficult overstate the value of having a dataset as complete as what is reported here and collected at the scale that it was collected, for evaluating patterns of impairment and linking it to potential environmental stressors.

Most stream surveys are local in scale, with many collecting biological data and only a limited number of physico-chemical measures also collected. While informative for that particular stream or narrow region, these studies are limited in their capacity for making broad, general conclusions about diversity patterns and/or impairment. Additionally, many stream surveys are targeted, i.e., sampling sites where there is known impairment or where remediation efforts are being implemented, which limits the scope of findings and biases the types of questions that can be addressed. Likewise, because there are typically inconsistencies in methodologies, combining data from multiple surveys can be very problematic if not impractical for evaluating patterns at broader spatial scales and for making general observations. The ability to make broad, more generalizable conclusions requires surveys conducted at larger spatial scales employing consistent methodologies.

Based on a random sample of surveyed streams from across Washington, we conclude that approximately one third of all stream kilometers assessed were in poor biological condition as determined with macroinvertebrate communities. Unsurprisingly, we also observed regional differences in the proportion of streams determined to be in poor biological condition, with nearly 46% of streams assessed in the Columbia Plateau classified as impaired relative to regionally targeted reference sites. At even finer scales, the proportion of stream kilometers in poor biological condition was highest in the Puget Sound region and far eastern portions of the state, i.e., Northeast, Snake River and unlisted salmon recovery regions, where in each of these regions we observed over 40 percent of stream kilometers assessed as being in poor biological condition. The Puget Sound is dominated largely by urban influences, namely the Seattle-Tacoma metropolitan area, while eastern Washington has lower population densities, yet receives far less precipitation than western portions of the state and is strongly influenced by agricultural practices. However, it is conceivable that our data actually underestimate the proportion of streams in poor biological condition within the Puget Sound region; the GRTS design provides a spatially balanced random sample within a region and given that urban influences in this region are quite spatially clumped, it is possible that our data set included few samples in highly urbanized areas.

We simultaneously measured a wide variety of physico-chemical and physical habitat parameters along with the biological data, which gave us the ability to evaluate the prevalence of possible impairment for multiple variables known to influence stream macroinvertebrate communities. We determined that many of the aquatic stressors with the greatest regional prevalence were those tied to substrate condition. Based on regional extent, four of the top six stressors evaluated were variables related to the condition of the substrate, with LRBS and percent sand/fines being the most prevalent. Additionally, the prevalence of poor condition across the state for other variables, including total nitrogen and low dissolved oxygen levels were also noteworthy.

Having co-occurring biological and environmental data allowed us to evaluate the potential influence of these variables on macroinvertebrate communities using conditional probabilities. Using RR analysis, we observed that poor B-IBI scores were four times more likely when observed with poor percent sand/fines. Other notable variables also associated with poor B-IBI scores were lead concentrations in sediment, proportion of canopy cover, conductivity, turbidity, chloride and total phosphorus. However, the frequency with which some of these variables were observed in poor condition was relatively low, e.g., lead, indicating that when these stressors were observed in poor condition, the probability of poor biological condition increased, yet given how infrequently some of these variables occurred in poor condition within our dataset, the problems associated with these variables could be considered of immediate concern when encountered rather than a general problem. However, one benefit of the AR analyses is the incorporation of relative extent and RR, which helps to identify key regional stressors and estimate the potential benefits of stressor remediation.

Our AR analyses determined that generally, for the regions which our samples encompassed, the greatest potential for improving poor biological condition for stream macroinvertebrates lies in improving substrate conditions, riparian canopy cover and nutrients. AR revealed that the top four stressors with the largest attributable risk were all measures related to condition of the substrate and that approximately 60% of stream kilometers now classified as being in poor biological condition could be improved if conditions relating to poor percent sand/fines were also improved. This estimate does not mean that biological condition at sites currently classified as poor would improve to the point where they would be considered to be in good condition, but that improvement would be such that they would no longer be classified as being in poor condition, i.e., either fair or good. This conclusion is based on the assumptions of causality and reversibility, which are the expectations that if a stressor is eliminated, the degree of ecosystem recovery will be commensurate (Van Sickle & Paulsen 2008). While these assumptions may not be completely reasonable in a practical sense, our findings still implicate poor substrate conditions as the most likely stressor contributing to poor macroinvertebrate community health in our dataset.

The findings that substrate conditions were important contributors to stream macroinvertebrate health were not surprising, yet they are intuitive, as many sensitive stream invertebrate taxa (e.g., EPT taxa) require hard substrate with adequate interstitial spaces to thrive. Excessive inputs of fine sediments and sand to stream substrates can fill interstitial spaces, leading to a loss of functional habitat and shifts in community composition and/or biodiversity loss (Bryce et al. 2010; Burdon et al. 2013). In support of this reasoning, we observed that between biological condition classes, there was a distinct loss of taxa sensitive to fine sediment deposition as measured with the FSBI. We also observed a significant loss of sensitive taxa across biological condition classes as measured with EPT and intolerant taxa richness, respectively, while also observing a trend towards sensitive taxa being replaced by more tolerant ones. Given that multiple diversity measures responded predictably and consistently, speaks to the generality and applicability of our results outside our region of study. Additionally, EPT taxa richness, a common variable evaluated in many stream studies, was highly correlated with B-IBI scores (Pearson correlation coefficient = 0.95) in our dataset, which suggests that had we performed RR/AR on EPT richness, the findings would likely have been quite similar to those we observed using the B-IBI.

Many of the findings reported here are consistent with those from EPA's national stream surveys (e.g., Wadeable Streams Assessment and NRSA), which have found that nutrients, riparian vegetative cover and fine sediment are common stressors leading to poor biological condition in the western mountains and xeric west, which includes Washington (U.S. EPA 2016). Loss of riparian cover can contribute to elevated fine sediment deposition and nutrient inputs to streams, as well as increased flashy flows (Poff et al. 1997; Coles et al. 2012), all of which can negatively influence the composition and diversity of stream macroinvertebrate communities. Therefore, efforts aimed at preserving riparian buffers and maintaining/restoring stream flows which more closely mimic natural patterns would facilitate attempts to preserve stream biodiversity. Conversely, in highly impacted areas, efforts which help restore riparian vegetation and the natural flow regime, should reduce inputs of fine sediment, nutrients and various toxics into the stream channel, contributing to their restoration. Notably, given that fine sediment deposition can also increase in low gradient streams, poor B-IBI scores were not significantly associated with low slope in our dataset, suggesting that low stream gradient by itself was not a major contributing factor to poor biological condition. Additionally, elevated nutrient inputs and increased light resulting from loss of riparian cover can also lead to increased probability of nuisance algal growth in streams, which may reduce habitat complexity (i.e., fill interstitial spaces) and negatively impact aquatic biota. Nutrients, particularly phosphorus, have been observed to be increasing in the U.S., contributing to a significant loss of oligotrophic streams (Stoddard et al. 2016) and highlighting the need to increase efforts to monitor and evaluate nutrient inputs to streams.

5. Conclusion

Whether measured as the percent sand/fines in the substrate, relative bed stability, or average substrate size, data from the first statewide stream biological survey of perennial streams in Washington State suggests the most prevalent stressors negatively impacting macroinvertebrate communities are poor substrate conditions. These results were corroborated with observations of reductions in taxa sensitive to fine sediment deposition and a losses of EPT taxa in sites with poor biological condition. All of this information has the potential for informing those entities charged with managing streams, as it suggests that generally, the most successful approaches for maintaining or improving biodiversity and biological condition of macroinvertebrate communities will be through effective management of those factors influencing substrate conditions, namely reducing the amount of fine sediment entering stream channels.

Acknowledgements

Funding for sampling targeted reference sites came from several U.S. EPA 106 grants awarded to the Environmental Assessment Program at the Washington State Department of Ecology. We thank the Amnis Opes Institute for collecting much of the data from the probabilistic randomly sampled sites. We thank Tony Olsen for developing the GRTS master sample list. We also thank Chris Hartman, Niamh O’Rourke, Jenny Wolfe, Dan Dugger, Eiko Urmos-Berry, and Mitch Wallace for involvement in sampling targeted reference sites. The authors declare that they have no conflicts of interest. The ideas in this article are our own and do not represent policy or recommendations of the U.S. EPA.

References

Allan, J.D. 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. *Annual Review of Ecology, Evolution, and Systematics* 35: 257-284.

Bryce, S.A., Lomnicky, G.A., and P.R. Kaufmann. 2010. Protecting sediment-sensitive aquatic species in mountain streams through the application of biologically based streambed sediment criteria. *Journal of the North American Benthological Society* 29: 657-672.

Burdon, F.J., McIntosh, A.R., Harding, J.S. 2013. Habitat loss drives threshold response of benthic invertebrate communities to deposited sediment in agricultural streams. *Ecological Applications* 23: 1036-1047.

Coles, J.F., McMahon, G., Bell, A.H., Brown, L.R., Fitzpatrick, F.A., Eikenberry, B.C.S., Woodside, M.D., Cuffney, T.F., Bryant, W.L., Cappiella, K., Fraley-McNeal, L. 2012. Effects of Urban Development on Stream Ecosystems in Nine Metropolitan Study Areas Across the United States (No. 1373). US Geological Survey.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.I., Knowler, D.J., Lévêque, C., Naiman, R.J., Prieur-Richard, A.H., Soto, D., Stiassny, M.L. and Sullivan, C.A., 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological reviews* 81: 163-182.

Karr, J.R. 1998. Rivers as sentinels: using the biology of rivers to guide landscape management. In: Naiman, R.J., Bilby, R.E. (Eds.), River Ecology and Management: Lessons from the Pacific Coastal Ecoregion. Springer, New York, pp. 502-528.

Kincaid, T.M. and Olsen, A.R. (2016). spsurvey: Spatial Survey Design and Analysis. R package version 3.3). R Core Team (2017).

Kuemmerlen, M., Schmalz, B., Cai, Q., Haase, P., Fohrer, N. and Jähnig, S.C., 2015. An attack on two fronts: predicting how changes in land use and climate affect the distribution of stream macroinvertebrates. *Freshwater Biology* 60: 1443-1458.

Marshalonis, D. and Larson, C.A. 2018. Flow pulses and fine sediments degrade stream macroinvertebrate communities in King County, Washington, USA. Ecological Indicators 93: 365-378. https://doi.org/10.1016/j.ecolind.2018.04.060.

Michelsen, T. 2011. Development of benthic SQVs for freshwater sediments in Washington, Oregon, and Idaho. Washington State Department of Ecology. Publication No. 11-09-054.

Morley, S.A. and Karr, J.R. 2001. Assessing and restoring the health of urban streams in the Puget Sound Basin. *Conservation Biology* 16: 1498-1509.

Osborne, L.L., Bayley, P.B., Higler, L.W.G., Statzner, B., Triska, F., and Moth Iversen, T. 1993. Restoration of lowland streams: an introduction. *Freshwater Biology* 29: 187-194.

Paul, M.J. and Meyer, J.L. 2001. Streams in the urban landscape. *Annual Review of Ecology and Systematics* 32: 333-365.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C. 1997. The natural flow regime. *Bioscience* 47: 769–784.

Pyne, M.I. and Poff, N.L., 2017. Vulnerability of stream community composition and function to projected thermal warming and hydrologic change across ecoregions in the western United States. *Global Change Biology* 23: 77-93.

R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Relyea, C.D., Minshall, G.W., Danehy, R.J., 2012. Development and validation of an aquatic fine sediment biotic index. *Environmental Assessment* 49: 242–252.

Rosburg, T.T., Nelson, P.A. and Bledsoe, B.P., 2017. Effects of urbanization on flow duration and stream flashiness: a case study of Puget Sound streams, western Washington, USA. *JAWRA Journal of the American Water Resources Association*, 53: 493-507.

Stevens, D.L., Jr. and Olsen, A.R. 2004. Spatially-balanced sampling of natural resources. *Journal of the American Statistical Association* 99: 262-278.

Stoddard, J.L., Van Sickle, J., Herlihy, A.T., Brahney, J., Paulsen, S., Peck, D.V., Mitchell, R. and Pollard, A.I., 2016. Continental-scale increase in lake and stream phosphorus: Are oligotrophic systems disappearing in the United States?. *Environmental Science & Technology*, 50: 3409-3415.

U.S. EPA. 2000. Stressor Identification Guidance Document. EPA/822/B-00/025. Office of Water, Office of Research and Development, Washington, DC, USA. Available at: http://www.epa.gov/waterscience/biocriteria/stressors/stressorid.html.

U.S. EPA. 2007. Causal Analysis/Diagnostic Decision Information System (CADDIS): www.epa.gov/caddis. Office of Research and Development, Washington, DC, 2017.

U.S. EPA. 2016. National Rivers and Streams Assessment 2008-2009: A Collaborative Survey. Office of Water and Office of Research and Development. Washington, DC. EPA/841/R-16/007.

Van Sickle, J., Stoddard, J.L., Paulsen, S.G. and A.R. Olsen. 2006. Using relative risk to compare the effects of aquatic stressors at a regional scale. *Environmental Management* 38: 1020-1030.

Van Sickle, J. and S.G. Paulsen. 2008. Assessing the attributable risks, relative risks, and regional extents of aquatic stressors. *Journal of the North American Benthological Society* 27: 920-931.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R. and Davies, P.M. 2010. Global threats to human water security and river biodiversity. *Nature* 467: 555-561.

Woodward, G., Perkins, D.M. and Brown, L.E., 2010. Climate change and freshwater ecosystems: impacts across multiple levels of organization. *Philosophical Transactions of the Royal Society B: Biological Sciences* 365: 2093-2106.

Yuan, L.L. and Norton, S.B. 2004. Assessing the relative severity of stressors at a watershed scale. *Environmental Monitoring and Assessment* 98: 323-349.

Table 1. Condition class thresholds for B-IBI and other potential stressors for three assessment regions in Washington State. Poor and good condition classes are defined in each cell, by the 1st and 2nd inequalities, respectively, with values between these two thresholds designated as fair condition. LRBS = log relative bed stability, DgmLog10 = average substrate size, LWDSiteVolume = volume of large woody debris.

Variable	Western WA	Eastern WA	Columbia Plateau
B-IBI (0-100)	49.98, 73.73	53.44, 63.0	36.37, 48.7
Water			
Conductivity (µS/cm)	162.25, 143.8	349.39, 117.65	309.24, 264.3
Dissolved Oxygen (mg/L)	9.77, 10.25	9.19, 9.7	7.44, 8.81
pH (Low)	6.5, 7.0	6.5, 7.0	6.5, 7.0
pH (High)	8.5, 7.5	8.5, 7.5	8.5, 7.5
Water Temperature (°C)	15.06, 13.65	14.2, 12.0	20.14, 17.23
Turbidity (NTU)	4.475, 1.73	9.96, 2.7	20.47, 15.95
Chloride (mg/L)	12.45, 5.61	1.86, 0.74	13.72, 6.07
Total Nitrogen (µg/L)[a]	229, 131	229, 131	462, 246
Total Phosphorus (µg/L)[a]	36, 14	36, 14	70, 36
Total Suspended Solids (mg/L)	5.47, 2	22.65, 6.0	44.4, 11.33
Sediment[b]			
Arsenic (mg/Kg)	33, 9.8	33, 9.8	33, 9.8
Copper (mg/Kg)	149, 32	149, 32	149, 32
Lead (mg/Kg)	128, 36	128, 36	128, 36
Zinc (mg/Kg)	459, 120	459, 120	459, 120
Total PAHs	22800, 1610	22800, 1610	22800, 1610
Habitat			
DgmLog10	0.80, 1.37	-0.08, 0.69	0.03, 0.98
LRBS	0.26, -0.21	-0.28, -0.66	-0.51, -0.44
Reach Slope %	0.5, 2	0.5, 2	0.5, 2
Sinuosity	1.06, 1.11	1.03, 1.09	1.03, 1.09
Sand/Fines %[c]	25.5, 15.5	25.5, 15.5	25.5, 15.5
Embededness %	46.93, 35.10	70.27, 54.38	63.99, 45.63
LWDSiteVolume (m^3)	16.87, 49.8	3.38, 9.91	0.32, 1.98
Canopy Cover (proportion)	0.87, 0.95	0.93, 0.98	0.46, 0.82

[a] Criteria set using values from Wadable Streams Assessment (Van Sickle and Paulsen 2008)
[b] Sediment Quality Standard/Screening Level 1 values from Michelsen 2011 (Arsenic = 14 $mg \cdot Kg^{-1}$, Copper = 400 $mg \cdot Kg^{-1}$, Lead = 360 $mg \cdot Kg^{-1}$, Zinc = 3200 $mg \cdot Kg^{-1}$, Total PAHs = 17,000 $\mu g \cdot Kg^{-1}$)
[c] Criteria set using EMAP West survey (Bryce et al. 2010)

Figure captions

Figure 1. (a) Random and reference sites sampled in 7 Salmon Recovery Regions and (b) three assessment regions.

Figure 2. (a) Number of stream kilometers assessed as either good, fair, or poor biological condition based on B-IBI scores for all sites in Washington and (b) for each of the assessment regions. Percent of kilometers for each category are presented next to error bars. Error bars represent 95% confidence intervals.

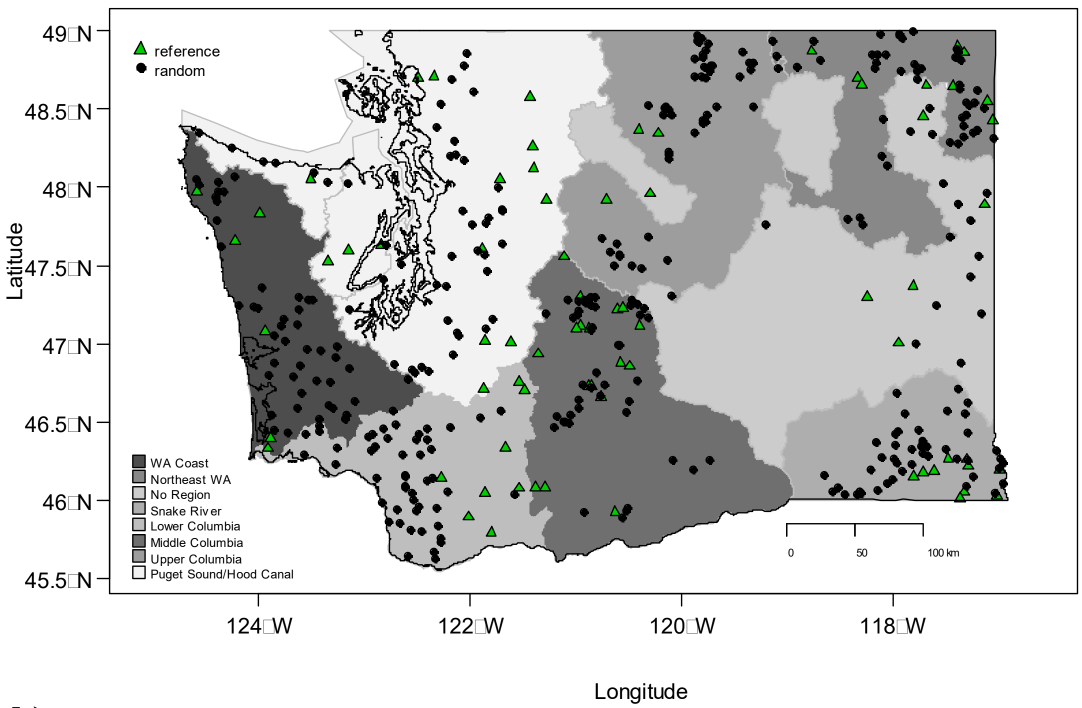
Figure 3. Number of stream kilometers assessed as either good, fair, or poor biological condition based on B-IBI scores for seven Salmon Recovery Regions and an unlisted region in Washington. Percent of kilometers for each category are presented next to error bars. Error bars represent 95% confidence intervals.

Figure 4. Percent of stream kilometers determined to be in poor condition for various chemical and physical habitat stressors. Condition determined relative to regional reference sites. Values next to error bars represent the number of sites determined to be in poor condition. Error bars represent 95% confidence intervals.

Figure 5. (a) Relative risk analysis, where values greater than one indicate an increased risk of poor B-IBI scores associated with poor conditions of the evaluated environmental parameters and (b) attributable risk analysis, where values greater than zero indicate the proportion of stream kilometers assessed that could be improved to ‘not poor’ if the environmental parameter were improved. Light colors indicate variables with significant impacts and error bars represent 95% confidence intervals.

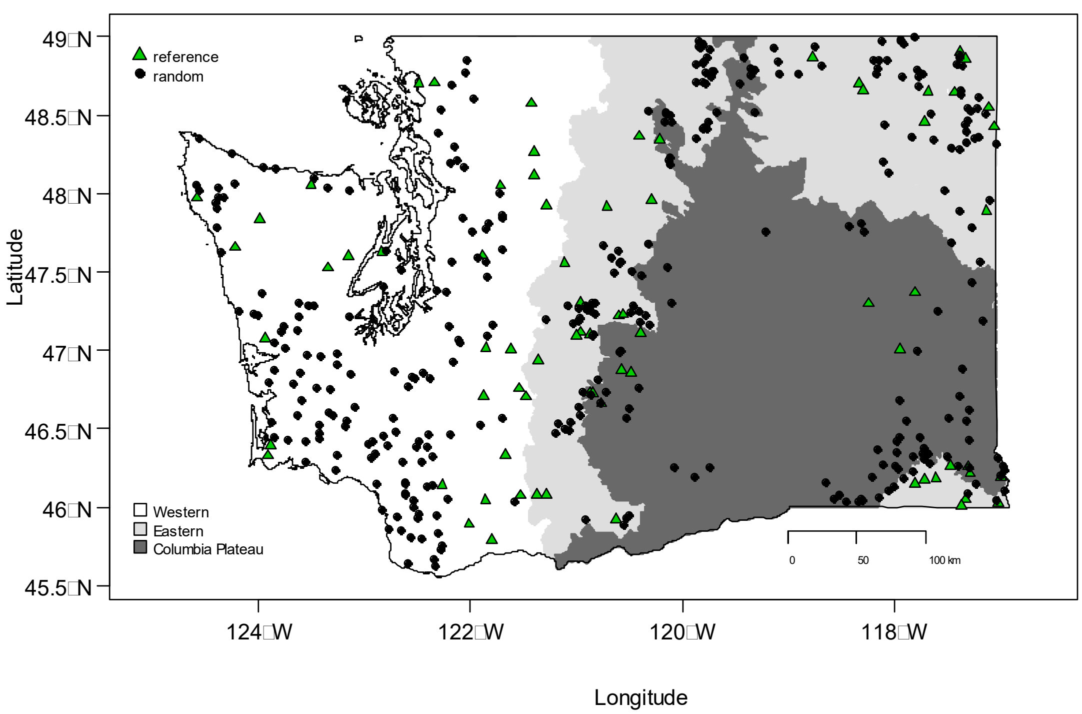
Figure 6. (a) Average FSBI scores (low values indicate loss of taxa sensitive to fine sediment deposition) (b) EPT taxa richness, (c) intolerant taxa richness, and (d) percent tolerant taxa for sites classified as ‘good’, ‘fair’, ‘poor’ based on B-IBI scores. Error bars represent 95% confidence intervals. Letters denote statistically significant differences between groups.

a)



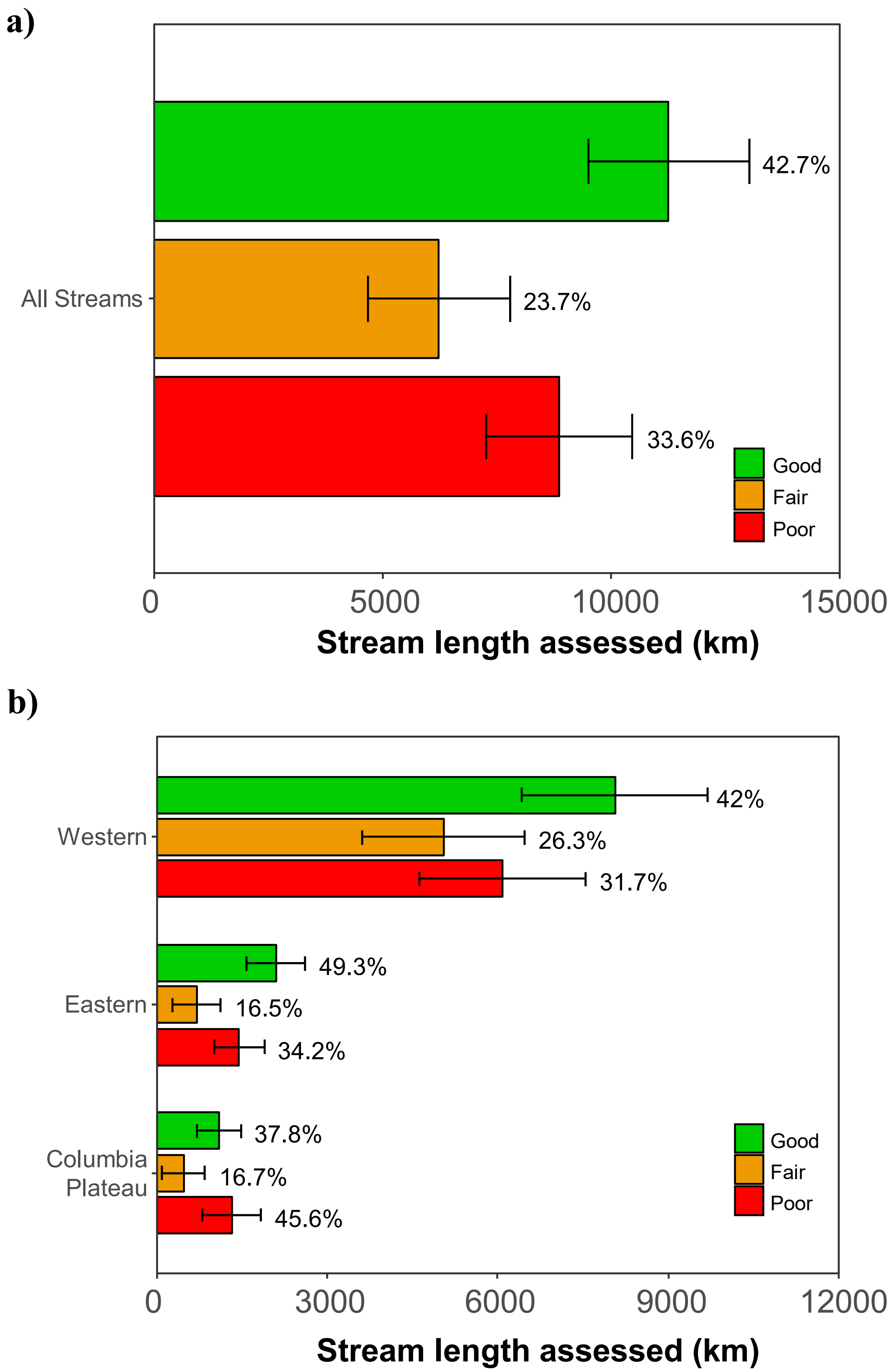
reference
random
WA Coast
Northeast WA
No Region
Snake River
Lower Columbia
Middle Columbia
Upper Columbia
Puget Sound/Hood Canal
0
50
100 km
Latitude
Longitude
49□N
48.5□N
48□N
47.5□N
47□N
46.5□N
46□N
45.5□N
124□W
122□W
120□W
118□W

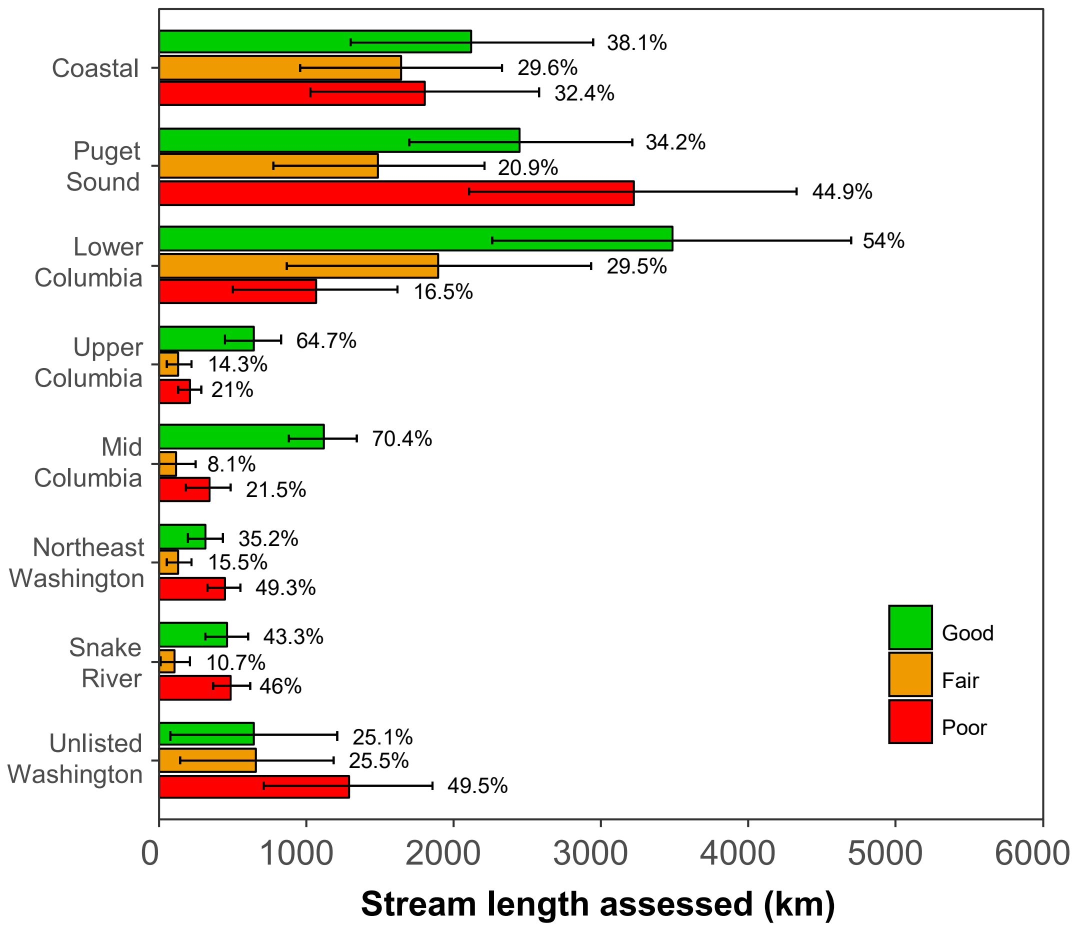
b)



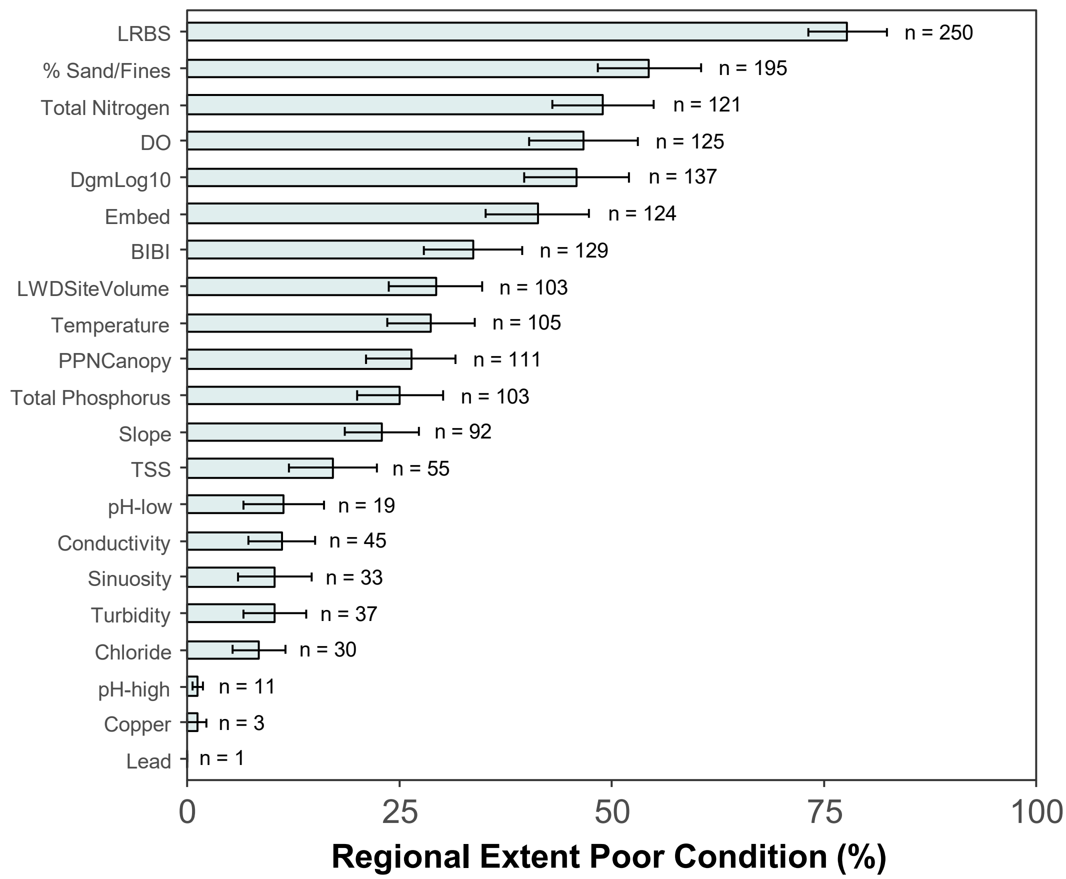
reference
random
Western
Eastern
Columbia Plateau
0
50
100 km
Latitude
Longitude
49□N
48.5□N
48□N
47.5□N
47□N
46.5□N
46□N
45.5□N
124□W
122□W
120□W
118□W

489

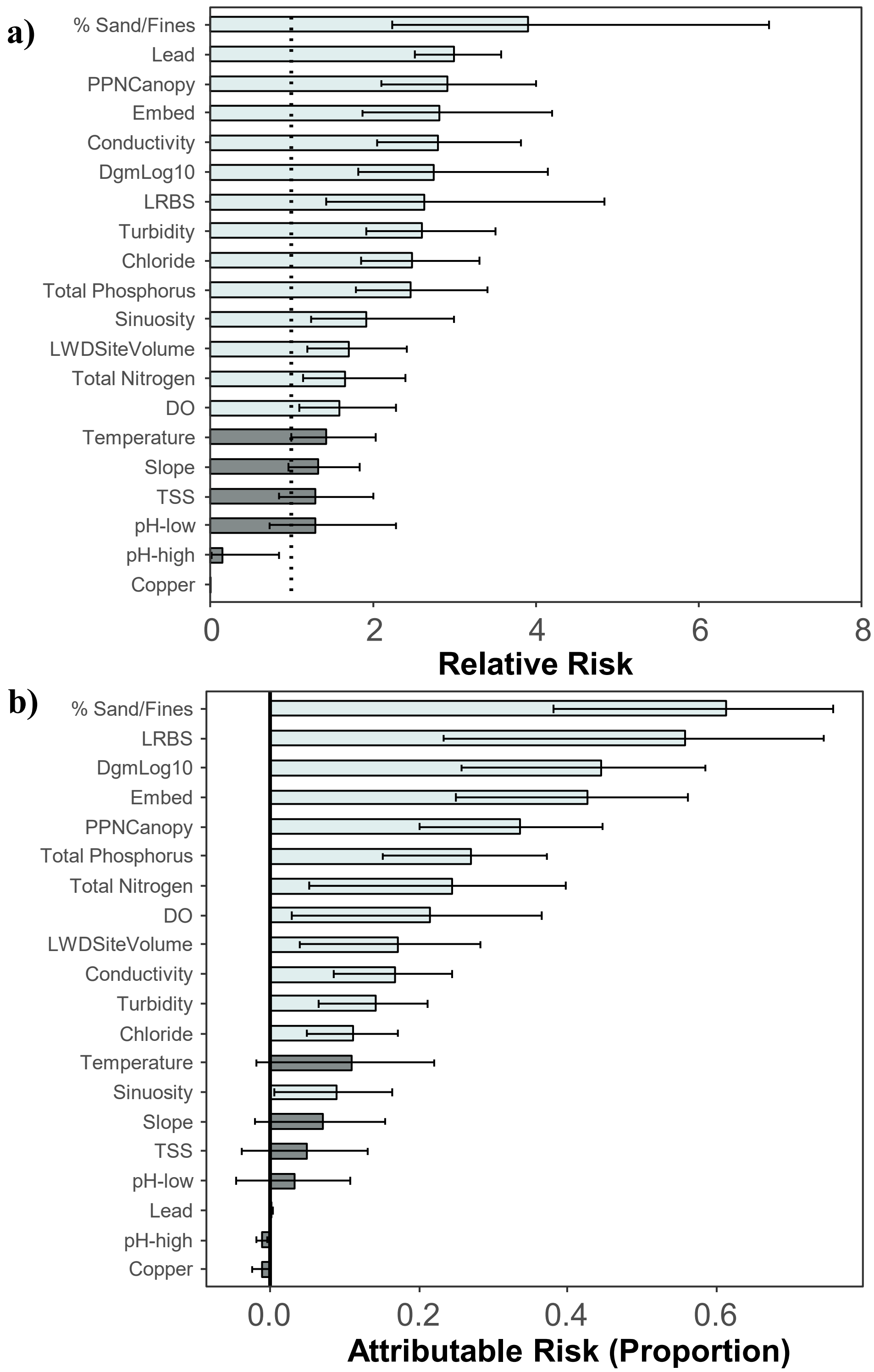

a)
All Streams
42.7%
23.7%
33.6%
Good
Fair
Poor
0
5000
10000
15000
Stream length assessed (km)
b)
Western
Eastern
Columbia Plateau
42%
26.3%
31.7%
49.3%
16.5%
34.2%
37.8%
16.7%
45.6%
Good
Fair
Poor
0
3000
6000
9000
12000
Stream length assessed (km)

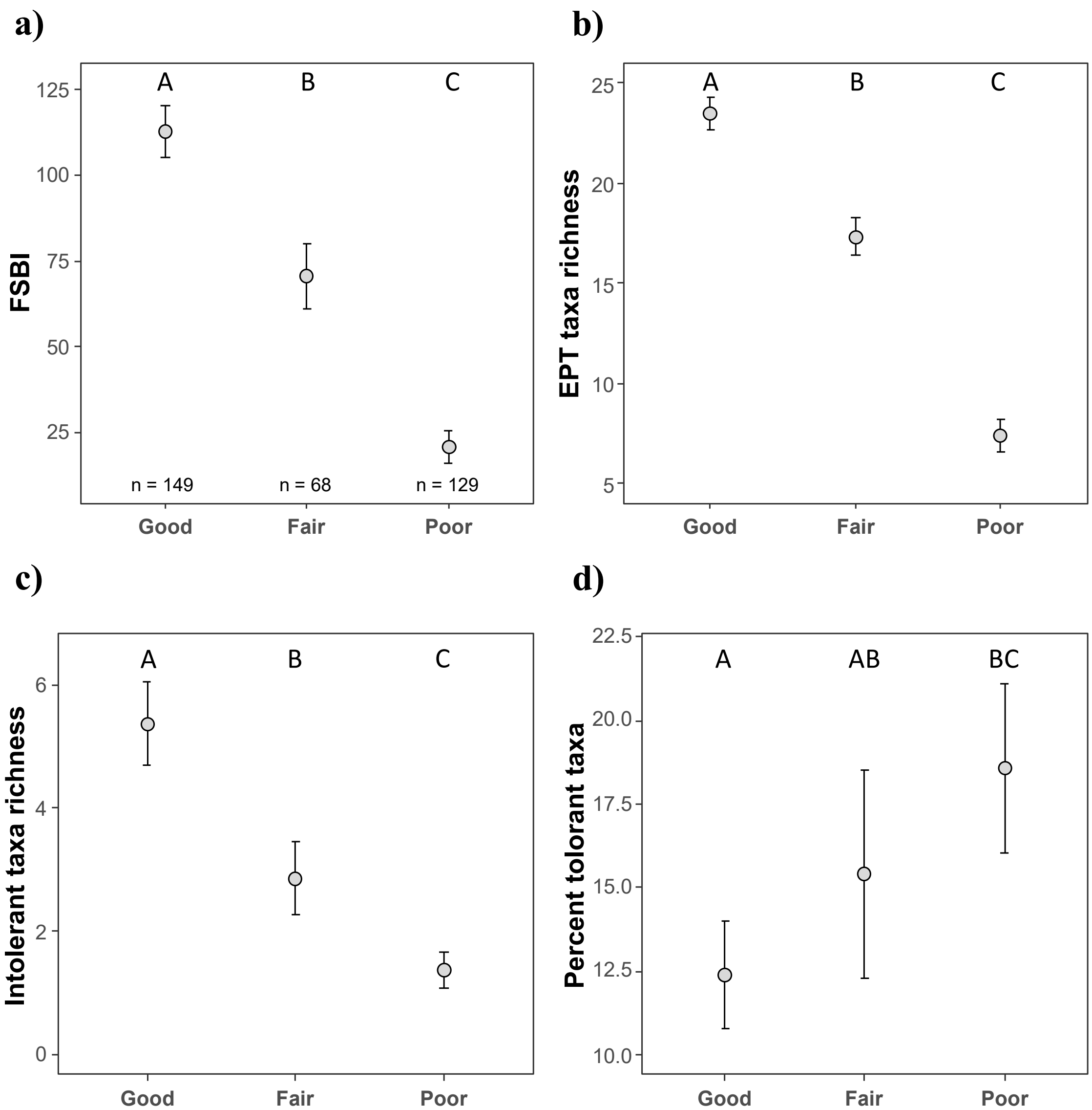


Coastal
Puget Sound
Lower Columbia
Upper Columbia
Mid Columbia
Northeast Washington
Snake River
Unlisted Washington
38.1%
29.6%
32.4%
34.2%
20.9%
44.9%
54%
29.5%
16.5%
64.7%
14.3%
21%
70.4%
8.1%
21.5%
35.2%
15.5%
49.3%
43.3%
10.7%
46%
25.1%
25.5%
49.5%
Good
Fair
Poor
0
1000
2000
3000
4000
5000
6000
Stream length assessed (km)



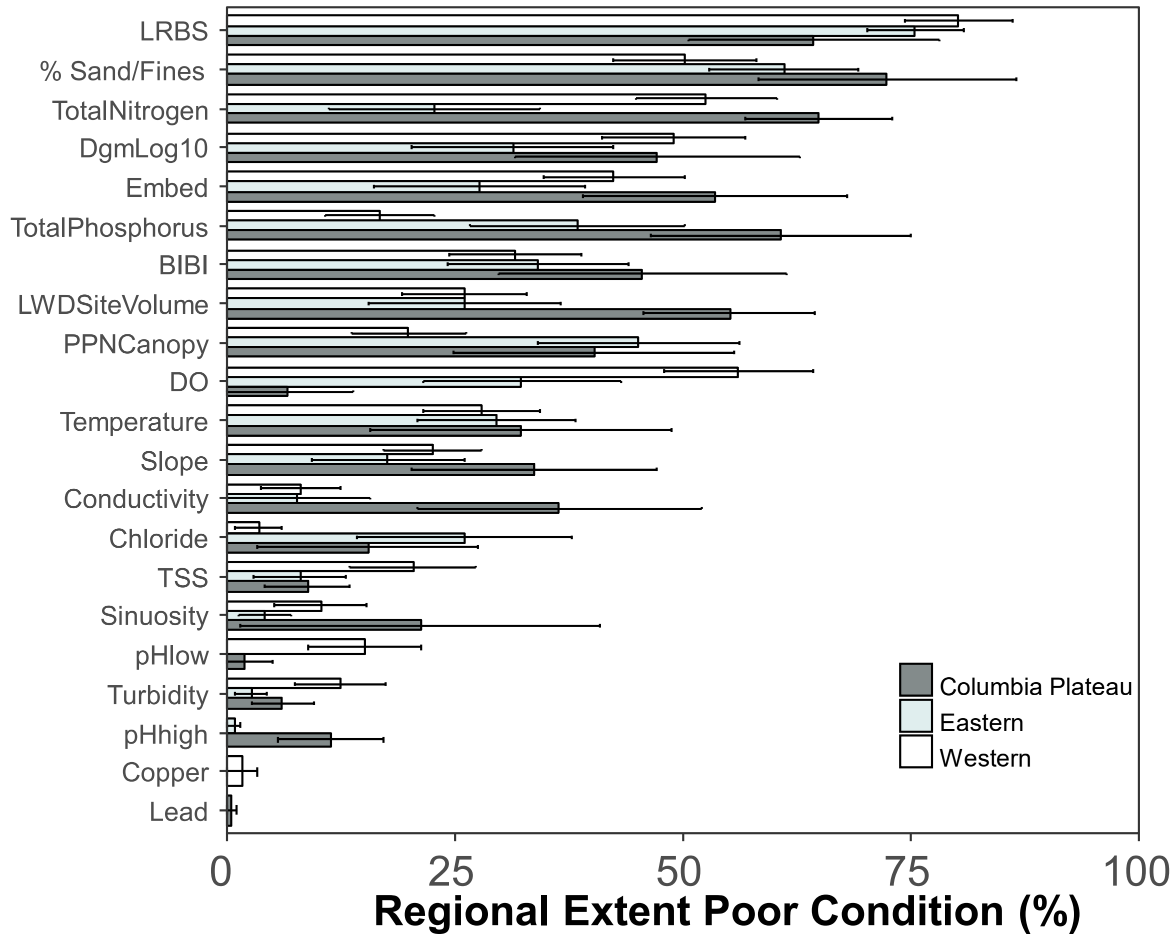
LRBS
% Sand/Fines
Total Nitrogen
DO
DgmLog10
Embed
BIBI
LWDSiteVolume
Temperature
PPNCanopy
Total Phosphorus
Slope
TSS
pH-low
Conductivity
Sinuosity
Turbidity
Chloride
pH-high
Copper
Lead
n = 250
n = 195
n = 121
n = 125
n = 137
n = 124
n = 129
n = 103
n = 105
n = 111
n = 103
n = 92
n = 55
n = 19
n = 45
n = 33
n = 37
n = 30
n = 11
n = 3
n = 1
0
25
50
75
100
Regional Extent Poor Condition (%)


a)
% Sand/Fines
Lead
PPNCanopy
Embed
Conductivity
DgmLog10
LRBS
Turbidity
Chloride
Total Phosphorus
Sinuosity
LWDSiteVolume
Total Nitrogen
DO
Temperature
Slope
TSS
pH-low
pH-high
Copper
0
2
4
6
8
Relative Risk
b)
% Sand/Fines
LRBS
DgmLog10
Embed
PPNCanopy
Total Phosphorus
Total Nitrogen
DO
LWDSiteVolume
Conductivity
Turbidity
Chloride
Temperature
Sinuosity
Slope
TSS
pH-low
Lead
pH-high
Copper
0.0
0.2
0.4
0.6
Attributable Risk (Proportion)



a)
b)
c)
d)
FSBI
EPT taxa richness
Intolerant taxa richness
Percent tolorant taxa
A
B
C
AB
BC
n = 149
n = 68
n = 129
Good
Fair
Poor

Supplementary material



Supplementary Figure 1. Percent of stream kilometers in each assessment region determined to be in poor condition for various chemical and physical habitat stressors. Condition determined relative to regional reference sites. Error bars represent 95% confidence intervals.